

GOPEX: A Laser Uplink to the Galileo Spacecraft on Its Way to Jupiter

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ABSTRACT

In the Galileo Optical Experiment (GOPEX), optical transmissions were beamed to the Galileo spacecraft by Earth-based transmitters at Table Mountain Observatory (TMO), California, and Starfire Optical Range (SOR), New Mexico. The demonstration took place over an eight-day period (December 9 through December 16) as Galileo receded from Earth on its way to Jupiter. At 6 million kilometers (15 times the Earth-Moon distance), the laser beam sent from Table Mountain Observatory eight days after Earth flyby covered the longest known range for laser transmission and detection,

1. INTRODUCTION

The second flyby of Earth, part of the Galileo spacecraft's Venus-Earth-Earth Gravity Assist (VEEGA) trajectory,¹ afforded a unique opportunity to perform a deep-space optical uplink with the spacecraft as it receded from Earth on its way to Jupiter. The Galileo Optical Experiment (GOPEX) was conducted over the period December 9 through December 16 from transmitter sites at Table Mountain Observatory (TMO), California, and at the Starfire Optical Range (SOR), New Mexico. The experiment had three principal objectives, namely:

- to demonstrate laser beam transmission to a spacecraft at deep-space distances
- to verify laser-beam pointing strategies applicable to an optical uplink based solely on spacecraft ephemeris predicts
- to validate the models developed to predict the performance of the optical link

Galileo's trajectory after its second Earth flyby, with a phase angle of approximately 90° (Sun-Earth-spacecraft), permitted the laser beam to be transmitted against a dark-Earth background. This nighttime laser uplink—GOPEX was conducted between 3:00 a.m. and 6:00 a.m. Pacific Standard Time—had two distinct advantages:

- It allowed the uplink to be performed at the frequency-doubled Nd:YAG laser wavelength of 532 nm, where the responsivity of the solid-state imaging (SS1) camera is high.
- It allowed long-exposure camera frames to be taken, which facilitated the identification of the detected laser transmissions. Analysis of the stray-light intensity in the focal plane of the camera showed that the camera shutter could remain open for up to 800 milliseconds before the scattered light from the bright Earth saturated the pixels that imaged the laser uplink.

By scanning the camera across the Earth, parallel to the Earth's terminator, during each exposure, the laser signal was readily distinguished from spurious noise counts in the camera frame. With this strategy, the laser uplink appeared as a series of evenly spaced bright dots within the camera frame, quite distinct from other features in the frame.

GOPEX was a very successful experiment. Frames of laser uplink data were received on each of the seven days of the experiment. (The demonstration covered a period of eight days, but other spacecraft activities precluded laser transmission on Day 5.) The laser uplink was detected on 48 of the 159 frames taken. Because of an unanticipated pointing bias in the scan platform direction, no pulses were detected on frames with exposure times less than 400 milliseconds. Inclement weather, aborted transmissions, and restrictions imposed by regulatory agencies and by the Project Galileo team accounted for the loss of data on the remaining frames.

2. GOPEX TRANSMISSION

2.1 Laser Transmitters

The laser transmitters at both sites consisted of a frequency-doubled Nd:YAG laser (532 nm) coupled to a Cassegrain telescope through a **coudé** mount **arrangement**. The transmitter characteristics are given in Table 1.

The TMO telescope used was the 0.6-meter equatorial-mount astronomical telescope that had been used in 1968 to perform the laser transmission to the Surveyor 7 spacecraft on the Moon. The telescope is f/36 at the **coudé** focus, and the appropriate beam-forming lens set was inserted into the **coudé** arm of the optical train (see Figure 1) to achieve the required laser beam divergence (see Table 1). In the optical-train design, the laser beam reflected off the 0.2-meter secondary mirror and illuminated a 12-centimeter **subaperture** on the telescope primary. The principal benefit of this **subaperture** illumination was that it eliminated the large loss in transmitted energy that would have been caused by occultation from the 0.2-meter secondary.

The two beam-forming lens sets, one for the **110-microradian** divergence and a second for the **60-microradian** divergence, were designed so that the laser beam was brought to a focus at a distance of 1.3 kilometers when the telescope was focused at infinity. Light from the reference stars used to point the telescope to Galileo was collected across the **full** 0.6-meter collecting aperture of the instrument.

The SOR telescope used for GOPEX was the 1.5-meter system that is used for adaptive-optics experiments at this facility. A thin-film-plate polarizer served as the aperture-sharing element, and coupled the laser output to the telescope optical train while allowing reference stars to be observed by the charge-coupled device (**CCD**) camera positioned in the orthogonal leg of the optical train. The required laser beam divergence was achieved by focusing the outgoing laser beam at ranges of 40 kilometers and 20 kilometers, corresponding to **40-microradian** and **80-microradian** beam divergence, respectively.

The output from the SOR laser was transmitted through the full 1.5-meter aperture of the telescope. The effects of occultation by the 10-centimeter secondary were mitigated by reconfiguring the laser resonator so that it generated a flat-top intensity profile across the **beam**. With this design, occultation by the secondary accounted for less than 10% of the transmission loss in the optical train.

2.2 GOPEX telescope-pointing strategy

The telescope-pointing files for both transmitter sites were generated from updates of the spacecraft ephemeris **file** that were provided to the GOPEX team on **December** 8 and December 11. The pointing strategy was to off-point the telescope from reference stars that were located within 0.5° of the spacecraft. Over the eight-day period, six guide stars of magnitudes 6 to 10 were used to point the TMO telescope to Galileo. The list of stars used is given in Table 2.

Table 1. GOPEX laser transmitter characteristics.

Characteristic	Table Mountain Observatory	Starfire Optical Range
Wavelength, nm	532	532
Pulse energy, mJ	250	350
Repetition rate, Hz	15-30	10
Pulse width, ns	12	15
Beam divergence, Wad		
Days 1-4	110	80
Days 6-8	60	40
Telescope mirror diameter		
Primary, m	0.6	1.5
Secondary, m	0.2	0.1
Optical train transmission	60%	43%

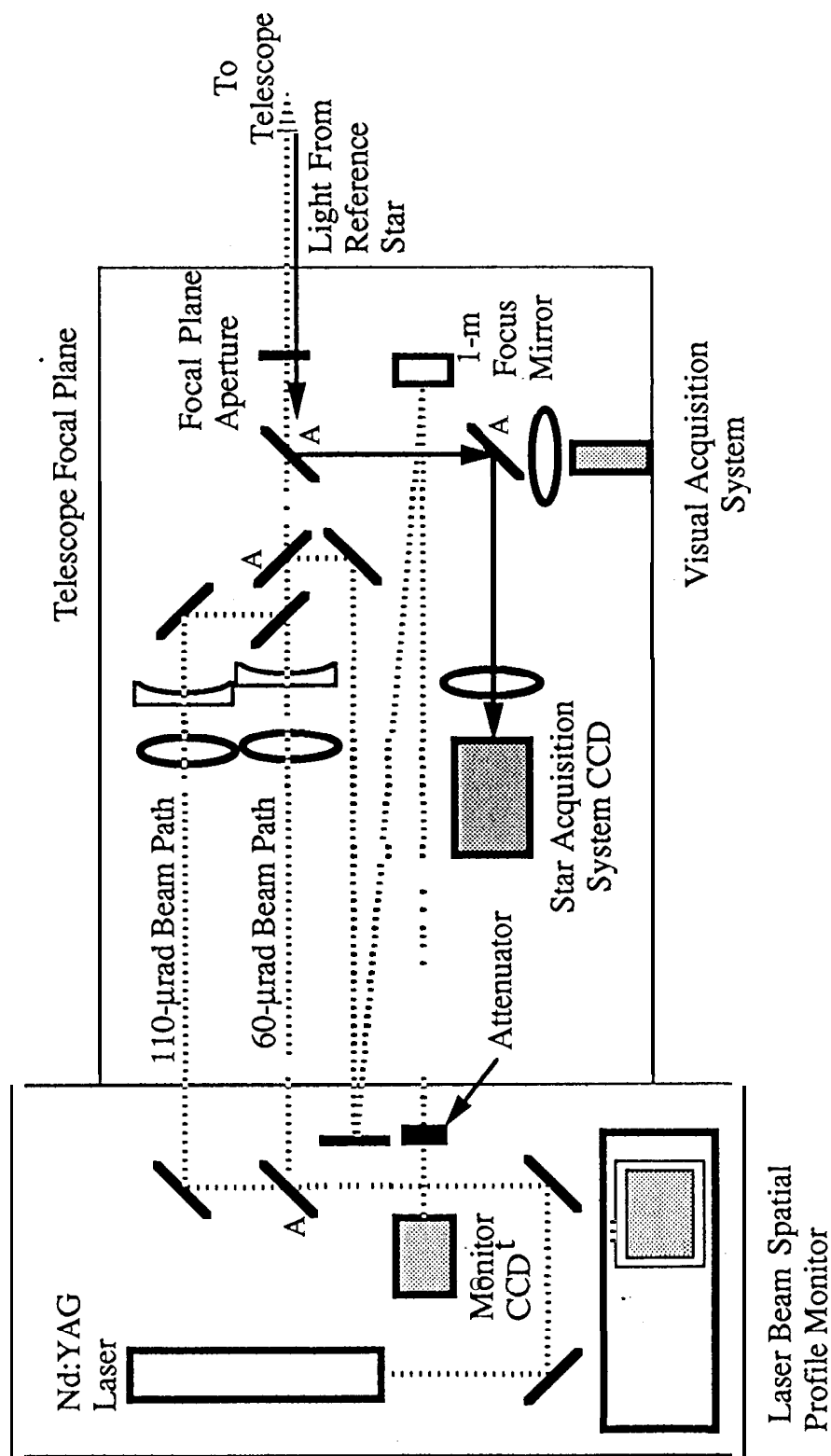


Fig. 1. GOPEX optical train, Table Mountain Observatory. Relay mirrors (labeled "A" in the figure) are appropriately inserted into the optical train to obtain the desired configuration.

Table 2. Table Mountain Observatory reference stars.

Day	Frames	Star number	Magnitude
1	1-50	938 ^a	10.35
	51-52	121 384 ^b	8.02
	54-60	None	Cloudy
2	1-40	121117 ^b	9.45
3	1-6	121199 ^b	8.77
	7-8	120456 ^b	6.39
	9-20	121 199 ^b	8.77
4	Weather precluded transmission		
5	No GOPEX uplink scheduled		
6	1-12	120799 ^b	8.39
7	1-10	120799 ^b	8.39
8	1-8	120799 ^b	8.39

^a B. M. Lasker, C. R. Sturch, B. J. McLean, J. L. Russell, H. Jenkner, and M. M. Shara, "The Guide Star Catalog. I. Astronomical Foundations and Image Processing," *Astronomical Journal*, Vol. 99, No. 6, pp. 2019-2058, June 1990.

^b T. E. Corbin and S. E. Urban, *Astrographic Catalogue Reference Stars*, U.S. Naval Observatory, Washington, D.C. 1991.

Transmission to Galileo was accomplished by using a "point and shoot" approach. In this technique, the telescope was set to track the reference star in the intervals between the three-second laser transmissions. Two and one-half minutes before laser transmission, the reference star was positioned in the center of the field of view of the focal plane aperture at coudé and the telescope was calibrated. Ten seconds prior to transmission, the telescope was pointed to Galileo's predicted location and set to track the spacecraft for the next thirteen seconds. This procedure was repeated during the three-minute to six-minute intervals between the laser transmissions. Because the telescope calibration was performed just before transmission, the pointing errors introduced by mount sag were reduced significantly. In addition, the high elevation of the spacecraft during the uplink-the experiment was conducted when Galileo's elevation from TMO was greater than 30°—and the proximity of the reference stars obviated the need to implement atmospheric refraction compensation techniques while pointing to the spacecraft.

To test the accuracy of the telescope-pointing predicts, a strategy was implemented by which SOR dithered the laser beam in a circle of 85-microradians radius about the predicted position of the spacecraft, while the TMO transmitter was kept pointed directly to the predicted position. This was done on the first day of GOPEX for several of the long-duration frames (frames with exposure times greater than 400 milliseconds). The results of this test are shown in Figure 2. Nine pulses can be clearly discerned in the figure; seven are from the 15-hertz TMO transmitter, and two are from the 10-hertz SOR transmitter. Without beam scanning, a total of four pulses would have been detected from the SOR transmitter. The presence of only two pulses from SOR and of seven from TMO clearly demonstrates that the error in the telescope pointing predicts was significantly less than 85 microradians. This was further confirmed by the successful use of a 60-microradian beam from TMO for laser transmissions on the last three days of GOPEX.

3. GOPEX RESULTS

A summary of the detected GOPEX laser transmissions over the duration of the experiment is given in Table 3. Over the eight-day period, transmissions to the spacecraft were made over a range beginning at 600,000 kilometers on the morning of December 9 and ending at 6,000,000 kilometers on the morning of December 16. Signals were successfully detected on each of the experiment days, although not on all frames within a given day. There were several reasons for the lack of detection on all frames. These included unfavorable weather (which caused outages), regulatory agency restrictions on transmissions, temporary

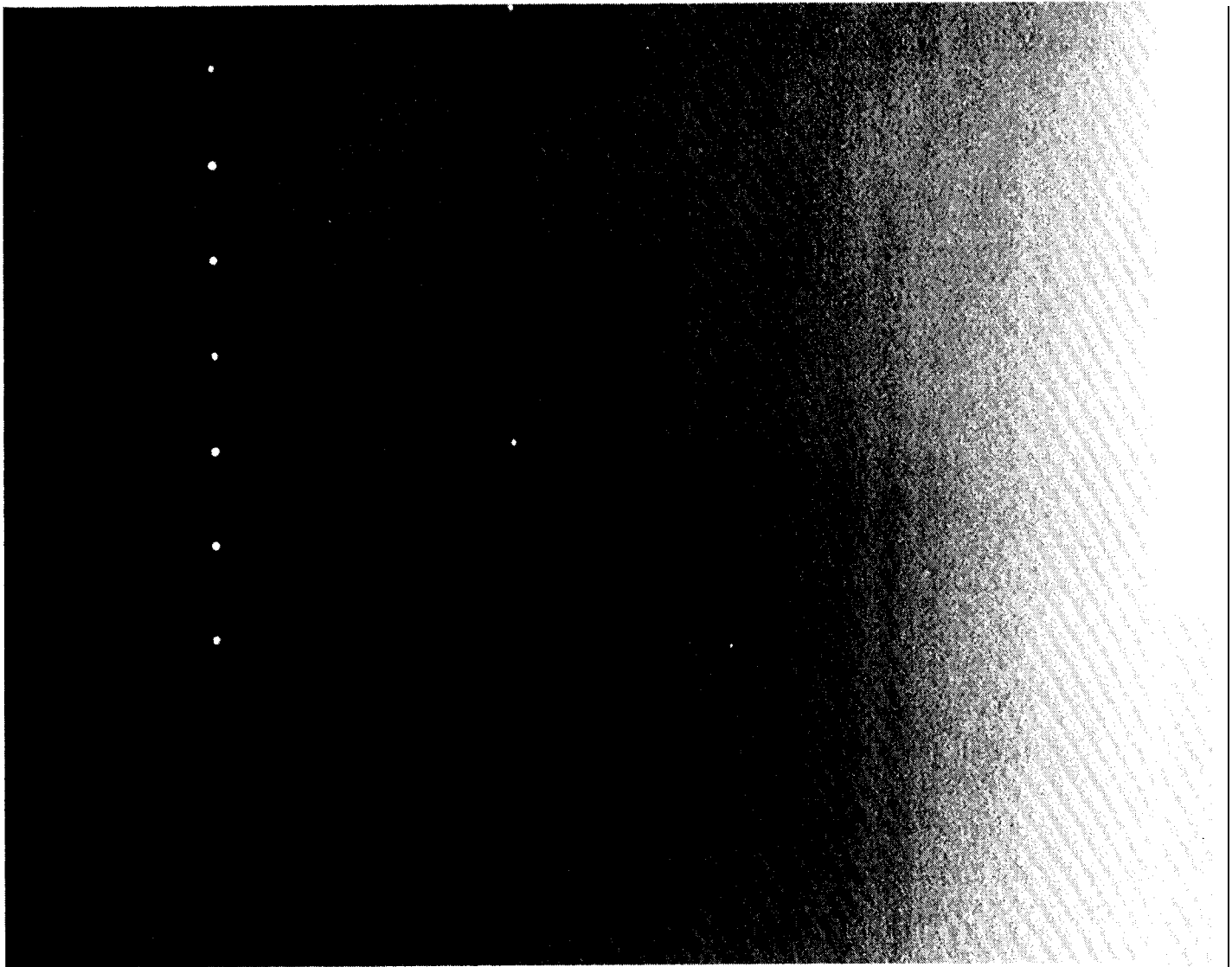


Fig. 2. Laser uplink from Starfire Optical Range and Table Mountain Observatory on Day 1 of GOPEX. The laser beam transmitted from Starfire Optical Range was scanned in an 85-microradian circle to evaluate the accuracy of the telescope pointing predicts.

signal-to-noise anomalies on the downlink, and an unexpected camera-pointing bias error. Preliminary results show unequivocally that successful detections were obtained on 48 camera images during the experiment window. Two representative images showing the detected laser pulses are shown in Figures 3 and 4.

Weather was the most severe impediment to successfully detecting the laser transmission. Winter storms at TMO and SOR brought snow, heavy clouds, and ground fog to these facilities. Transmission from TMO was most affected on the first and fourth days of the experiment. The last seven frames obtained on the first day were taken with TMO completely overcast and SOR in daylight. On the fourth day, falling snow at TMO precluded transmission from this facility; also on that day, during only one of the ten transmissions was there clear sky between the SOR transmitter and the spacecraft. Falling snow and heavy cloud cover prevented transmission from SOR on the last three days.

Restrictions from regulatory agencies were also responsible for data outages. Transmission of the GOPEX laser beam into space required the concurrence of the U.S. Space Defense Operations Center (SPADOC). On the first day, SPADOC

Table 3. Summary of **detected** laser signals.

Day	Shutter speed (ins)	Frames received	Frames with detections
1	133	9 of 10	0
	200	24 of 25	0
	400	19 of 20	11^b
	800	5 of 5	5
2	200	5 of 5	0
	267	15 of 15	0
	533	15 of 15	13
	800	5 of 5	5
3	200	5 of 5	0
	267	10 of 10	0
	533	5 of 5	5
4	200	3 of 3	1^{b,c}
	267	4 of 4	0
	533	3 of 3	1^c
5	No activity planned		
6^a	133	3 of 3	0
	267	6 of 6	0
	533	3 of 3	3
7^a	200	3 of 3	0
	400	3 of 4	3
	800	3 of 3	3
8^a	267	2 of 2	0
	533	4 of 4	4
	800	2 of 2	2

^a Adverse weather at **Starfire** Optical Range precluded laser transmission on this day.

^b Detection on some of the frames is tentative. The assessment of whether or not the **uplink** was **detected** is based on only one to three possible spots in the camera frame.

^c Adverse weather at Table Mountain Observatory precluded laser transmission on this day, and it was cloudy at **Starfire** Optical Range.

restrictions prevented TMO from transmitting during four frames. An additional frame was lost because the ground receiving station (at Goldstone, California) momentarily lost lock on the Galileo spacecraft downlink signal. Owing to the loss of downlink signal, the orientation of the spacecraft could not be confirmed, and since one of the GOPEX concurrence conditions was that laser **uplink** would **proceed** only if the spacecraft orientation was known, no laser transmissions were sent during this data outage.

During the **first** two days of **GOPEX**, the spacecraft orientation resulted in the low-gain antenna being pointed away from Earth. This resulted in a low signal-to-noise ratio (**SNR**) of the spacecraft **downlink** and was evidenced by the numerous burst errors in the data files. The GOPEX images for these days showed numerous streaks across the frames and made it difficult to discern successful laser transmissions on the images. On the second day, just after the **GOPEX** uplink, a planned spacecraft maneuver that increased the SNR of the radio frequency downlink was executed. This resulted in clearer GOPEX images for the remainder of the demonstration,

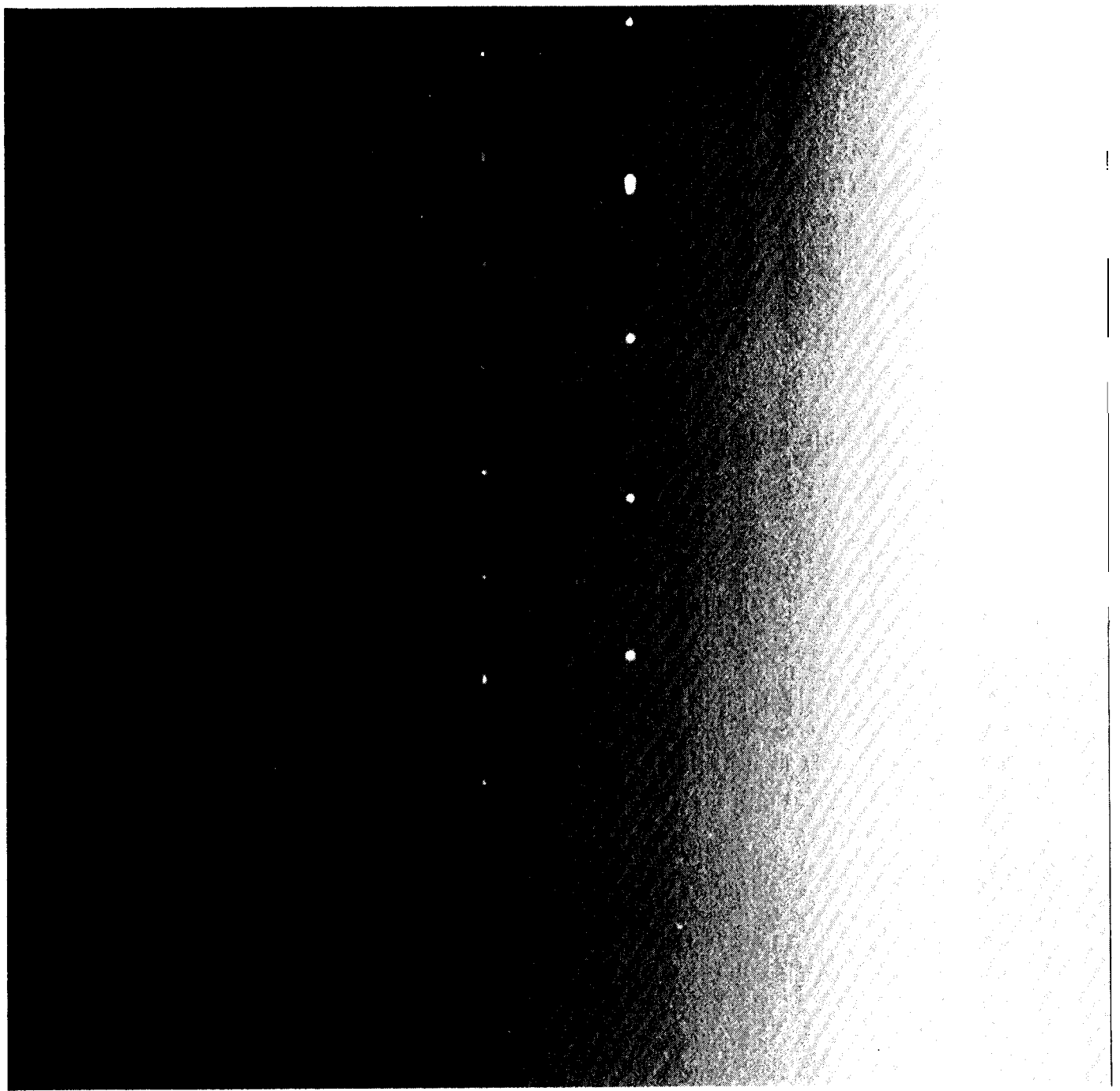


Fig. 3. Laser uplink from Table Mountain Observatory (15-hertz repetition rate) and Starfire Optical Range (10-hertz repetition rate) on Day 2 of GOPEX. The Starfire Optical Range uplink is closer to the bright Earth image than that of Table Mountain Observatory. The detected laser uplink is shown closer to the Earth's terminator (its bright edge).

The GOPEX demonstration required that the SS1 camera be operated in a mode for which it was not designed (that is, slewing the camera during imaging). To get the GOPEX transmitter sites in the field of view during the slew, the camera was initially pointed to a position above or below the targeted direction and the shutter was opened at a prescribed time after the start of the slew. Uncertainties in the stray-light intensity in the focal plane of the SS1 camera dictated the shutter times used for

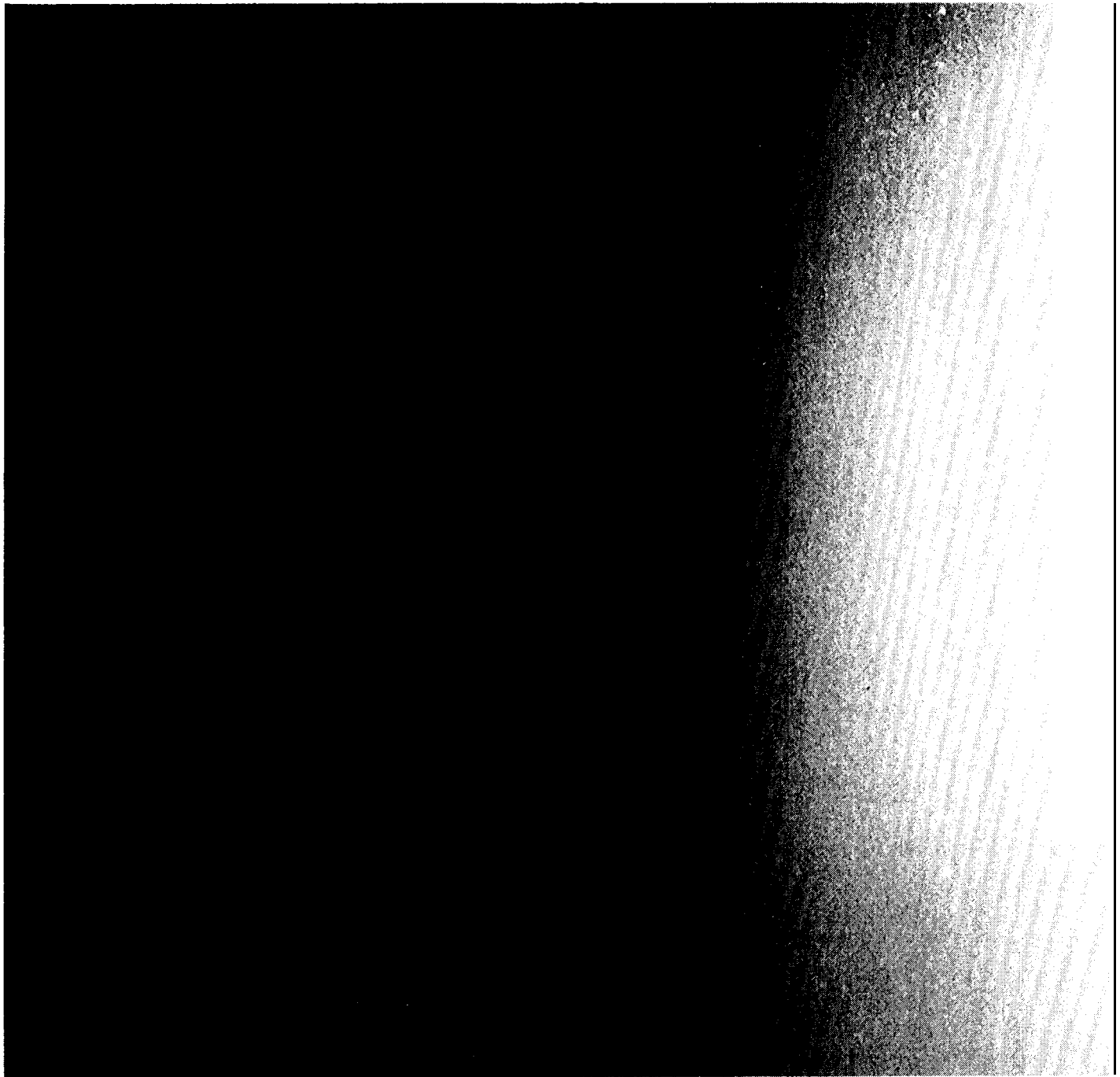


Fig. 4. Laser uplink from Table Mountain Observatory on Day 7. Inclement weather at Starfire Optical Range precluded laser transmission from there.

GOPEX. The times chosen ranged from 133 milliseconds to 800 milliseconds, and these were loaded into the spacecraft sequence of events prior to GOPEX. As the experiment progressed, it was observed that laser transmissions were detected only on frames with greater than 400-millisecond exposure times. This was traced to a pointing error caused by the scan platform acceleration being slower than predicted. As a result, no clear evidence of laser transmission was observed on the 90 frames taken with exposure times less than 400 milliseconds.

4. CONCLUSION

The results of the first deep-space optical transmission to a spacecraft in flight have been presented. The transmission was performed from transmitters located at TMO, California, and SOR, New Mexico. The **laser** uplink was detected on every day of the **experiment—out** to a range of 6,000,000 kilometers for the TMO transmission. The camera images returned from Galileo clearly show that two of the three experimental objectives were met. Preliminary analysis shows that the distribution of the detected-signal strengths is consistent with theoretical predictions.

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6. REFERENCE

1. K. E. Wilson, J. Schwartz, and J. **R. Lesh**, "GOPEX: A deep space optical communications experiment with the Galileo spacecraft," *SPIE Proceedings*, Vol. 1417, pp. 22–26, January 1991.